AD-A085 602 HARRY DIAMOND LABS ADELPHI MD F/G 18/3
A GUIDE TO THE ELECTROMAGNETIC PULSE HARDENING OF OPEN-WIRE SYS--ETC(U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A theoretical study of EMP response is presented for a family of open-wire systems. The goal is to provide the designer with an understanding of the performance of a number of hardening techniques. The hardening designs encompass both linear filter networks and filter-nonlinear component circuits. The results presented are a distillation of data from approximately 350 response curves. Although necessity demands

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20. Abstract (Cont'd)

a severe restriction in the number of permissible variables, the data are sufficiently informative to impart to the EMP systems designer an understanding of the level of effort necessary to harden an open-wire system.

CONTENTS

FIGURES

FIGURES

1. INTRODUCTION

An integral part of the Harry Diamond Laboratories (HDL) mission in the nuclear weapons effects area is the development of electromagnetic pulse (EMP) hardening criteria for Army systems. The purpose of this paper is to provide the designer of EMP protection hardware with some preliminary guidelines to hardening requirements for open-wire systems. The design of EMP protection hardware requires more the judicious application of developed and proven techniques than the search for new or novel approaches. As a first step in this development process, an understanding of the performance to be gained from various standard hardening approaches is essential. This requires

a. *A definition of the level of required hardening.* The criterion applied is the Army de facto standard of worst case. By worst case is meant a standard that represents a balance between a system configuration designed to maximize EMP coupling and a choice of realistic variables. The goal that should be reached is the development of reasonable hardening requirements.

b. *The selection of reasonable system configurations.* The present study is restricted to EMP penetration via open-wire circuits. Open-wire systems are significant because of their frequency of use and because they represent as severe a source of transient coupling as is typically encountered. The models were designed to encompass as broad a range in significant system variables as can be reasonably incorporated into a study of this nature while preserving sufficient simplicity that an understanding of model response is not lost in its complexity.

c. *The selection of realistic EMP protection networks.* This requires that all designs employ components that can be translated into hardware that is cost effective, size and weight restricted, and representative of what is available or in use.

This study provides the designer with an understanding of the magnitude of the open-wire hardening problem. It is meant as a "first-cut" design aid and is not, nor could a study of this scope ever be, a substitute for a rigorous development effort.

EMP protection hardware can be divided into two categories: filters and nonlinear devices. The latter include such components as nonlinear resistors (exemplified by the metal oxide varistor), spark gaps, and diodes. This study focuses on filters and a single member of the nonlinear component group — the metal oxide varistor. Among the significant EMP hardening devices untreated in this study is the spark arrester. Spark-gap design is not included for the following reasons:

a. The operational characteristics of spark gaps generally preclude their use on power lines, a large subclass of open-wire systems, except when incorporated with a series current-limiting element. For EMP protection, current-limiting elements (typically nonlinear resistors) negate the desirable characteristics of a spark arrester.

b. The theoretical treatment of spark gaps requires a detailed analysis of effects beyond the scope of this paper. To maximize the benefits of spark-gap design requires a study of

- The coupling between the complex antenna structure of the circuit to be protected and the radiation from the high-current spark-gap network.
- The coupling via the mutual inductance terms between all high-current elements and the protected circuits.
- To a lesser extent, coupling via the mutual capacitance terms. A discussion of spark gaps requires a detailed study of shielding between all high- and low-current members of a system, a study too dependent on system design to be amenable to a generalized discussion. (It should not be inferred that these effects are

unique to spark-gap circuits, but rather that a reasonable understanding of the full potential of spark-arrester performance demands a much broader analysis than other protection devices.)

Similarly, diodes are not explicitly addressed in this study. The large signal-handling capability required of an open-wire hardening network often precludes their use in any but a backup role to a primary protection circuit. In this mode, the diode circuit is generally mounted proximate to the circuit to be protected. For a properly designed hardening circuit, the peak voltage at the load can be readily determined from the design of this final-stage diode network. The only uncertainty is the survival of the diode protection network itself. Its required power-handling capability is very dependent on the design of the primary protection network and the nature of the EMP coupling source. Although this study is oriented towards an analysis of load response, the results can also be used to establish the power capability required of a secondary diode network — to this extent the present study addresses diode circuits.

2. SYSTEM CONFIGURATION AND COUPLING

This study is restricted to an analysis employing the high-altitude EMP environment specified by the U.S. Army Nuclear Agency.[1] FREFLD, a frequency-domain wire and cable coupling code, was used to calculate the response of the open-wire models to this environment. The resultant data were in the form of open-circuit voltage and short-circuit current waveforms — sufficient information to develop either a Thevenin or Norton equivalent circuit for the wire coupling source. All analysis employed a straight-wire geometry parallel to the ground and loaded at both ends in a manner representative of a realistic system. Six wire configurations were used: a 5-, 1-, and 0.1-km wire close to the earth and a 5-, 1-, and 0.1-km wire at a height of 5 m. The far end-wire loads represent the two extremes of open and short circuit as closely as can be satisfied by a simulated system. The model for the short circuit is that of a ground stake paralleled by the capacitance of a large tactical-shelter-sized load. The open circuit is represented by the capacitance to ground of a physically smaller wire load. Ground parameters typify the soil conditions of the U.S. east coast. Two EMP illumination conditions were chosen that, from previous systems-related experience, represent the worst-case threat: an end-fire vertically polarized illumination that maximizes the peak signal level and a broadside, horizontally polarized illumination that maximizes the coupled energy. These signals represent two extremes, with the end-fire case maximizing the coupling at the high-frequency end of the spectrum and the broadside case maximizing the coupling at the low-frequency end.

[1] [illegible] Research, Development and Acquisition, Nuclear [illegible] Criteria for Army Tactical Equipment (U), U.S. Army Nuclear Agency Report No. [illegible] August 1976 (CONFIDENTIAL)

To characterize the wire-coupling source, sufficient data are needed to generate either a Norton or Thevenin equivalent circuit. This requires the wire near-end open-circuit voltage and short-circuit current. A particularly simple source-impedance model can be developed from these data if only the early-time system response is required. For a time duration equal to twice the electrical length of the line, the source impedance is the impedance of the ideal, infinite line above ground. Since this condition is too restrictive for some of the EMP hardening designs, a more sophisticated late-time source impedance model is used. The open-wire system design is summarized in figure 1 (see page 7), a block diagram illustration and a representative equivalent circuit for a single configuration.

3. RESULTS

The EMP protection circuits analyzed are in figure 2. All analysis was performed using NET-2, a large-signal circuit analysis code. The 20-nH inductors included in most networks simulate a reasonable lead length inductance. Shunting capacitance was not included although it can be significant, particularly for poorly designed filter inductors. Series resistance for all filter inductors was fixed as 0.1 ohms, although for actual components the effective resistance can, depending on inductor design, become rather large over the

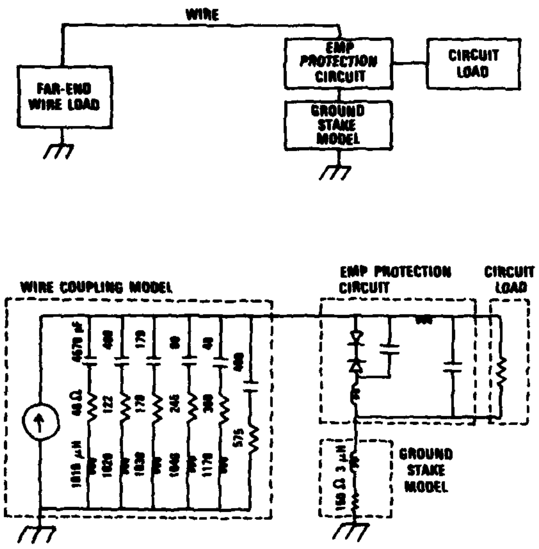
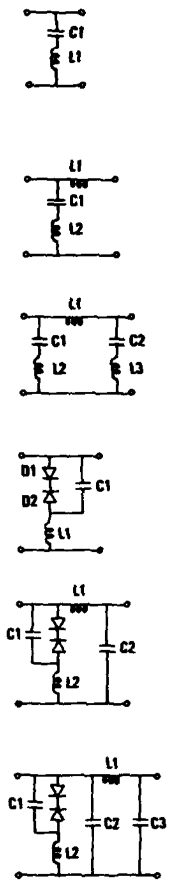


Figure 1. Block diagram and corresponding equivalent circuit for single configuration. Source impedance model depicted is for 1-km wire at 5 m height, with far-end load an open circuit.



C1	L1
0.01 μF	20 nH
0.1	20
1.	20
10.	20

C1	L1	L2
0.1 μF	0.1 μH	20 nH
1.	1.	20
10.	10.	20

C1	C2	L1	L2	L3
0.1 μF	0.1 μF	0.1 μH	20 nH	20 nH
1.	1.	1.	20	20
10.	10.	10.	20	20

C1	L1	D1 AND D2
2000 pF	20 nH	REVERSE BREAKDOWN VOLTAGE ≈ 9 kV DYNAMIC RESISTANCE = 1 ohm

C1	C2	L1	L2
2000 pF	0.1 μF	0.1 μH	20 nH
2000	1.	1.	20
2000	10.	10.	20

C1	C2	C3	L1	L2
2000 pF	0.1 μF	0.1 μF	0.1 μH	20 nH
2000	1.	1.	1.	20
2000	10.	10.	10.	20

Figure 2. EMP protection networks.

frequency range of interest. The assumption is that good EMP practices are employed in the design of these networks with sufficient shielding between all components — particularly between high- and low-current elements — that intercomponent field coupling is nonexistent. The network comprising the diodes and 2000-pF shunting capacitance is an equivalent circuit for a zinc-oxide surge arrester. This device was modeled because of its increasing use on commercial power lines. From among the wide range in available devices, the analysis was restricted to a single design representative of an available commercial unit.

The open-wire circuit load to be protected is restricted to a simple resistor with values of 1, 10, 1000, and 10,000 ohms.

Even with the severe limitations imposed on the number of permissible variables, it remains impractical to perform an analysis for which all quantities are varied in a systematic fashion. Rather, a representative choice of system configurations was employed to give a reasonable understanding of the performance of the protection circuits. The final data are contained in 350 time-domain curves representing the power and voltage responses of the open-wire circuit load.

To maximize the value of these data, it is desirable to correlate the calculated system response with realistic criteria for circuit damage. Circuit damage can result from any number of failure mechanisms. The dominant mechanism for EMP damage is a power-related failure of semiconductor devices. This mechanism dominates because of the common use of semiconductors in the front ends of military electronics and because

of the generally much lower failure threshold for semiconductors over other common circuit components. It has been demonstrated both experimentally and theoretically that the relationship between semiconductor component failure and dissipated power can be written as

$$K = Pt^n ,$$

where P is the peak power level to failure, t is the duration of the power pulse, and K is a constant characteristic of the device. The value of n varies between 0 and 1 and is dependent primarily on the duration of the power pulse and its polarity. Most P-N junctions display a markedly lower threshold to failure for a reverse-biased condition than for forward bias. For the pulse durations most frequently encountered with systems in an EMP environment, a good compromise value for n for a reverse bias condition is 0.5. To correlate with the large mass of semiconductor failure data available — data generally available in terms of the damage constant — results for circuit-load power dissipation are given in terms of the damage constant ($Pt^{1/2}$).

If one wishes to compare the results for the resistive circuit loads with the response of semiconductors (and a resistor under large signal conditions is not that unreasonable a model for a P-N junction), there is no rigorous approach. A measure of compromise is needed for correlating the complex power response of the circuit load with the response of components tested to the traditional square pulse. The approach adopted is to consider the circuit-load power response as a series of pulses defined by the zero crossing points and to operate upon the largest. Power is the peak pulse level, and time is the half-width of the pulse. This represents a reasonable approach, since the observed power response curves are invariably dominated by a single pulse. No attempt is made to fold together the response of the multiple pulses, since this would be equivalent for a P-N junction to incorporating the response of a series of alternating forward and reverse bias signals for which there is no rigorous justification (Duhamel's Theorem not withstanding).[2] For a limited number of circuit runs, where the duration of the pulse delivered to the resistive load is extremely long, data are given in terms of peak power only. All voltage response curves are reduced to peak values of voltage. Thus, the significant results of 350 response curves can be reduced to 24 graphs in a manner calculated not to overwhelm the reader. The damage constant and peak voltage data appear in figures 3 through 26 (see pages 9 through 14). The results in figures 13 and 25 represent an underestimate of the response of the circuit as previously defined, since proper circuit code operation demanded the inclusion of a resistor of several ohms in series with the filter inductor.

To further consolidate the damage constant data, the results of figures 3 through 26 are reduced to a histogram. Figure 27 (see page 15) is the damage constant population per decade for the data, with a superimposed histogram for the damage constant ($Pt^{1/2}$) of 51 diode and transistor types (base to collector and base to emitter) under reverse bias and fitted in the 0.1 to 10-μs range. Excluded from the histogram are those few data points demonstrating the generally insignificant variation of circuit response to the removal of all 20-nH lead inductors. A list of the diode and transistor types is given in the appendix. These experimental semiconductor data are for components designed into the front ends of a number of Army single and multichannel tactical radios and represent radio, field wire, and cable functions. All diode and transistor data were taken from the work of B. Kalab of Harry Diamond Laboratories (HDL).

4. CONCLUSION

The level of protection afforded a family of open-wire systems by a number of EMP hardening designs is demonstrated. From this effort emerges a general understanding of the response of open-wire systems to the Army defined high-altitude EMP environment criteria. While these results cannot be used to bypass the development effort necessary to design and test protection circuits, a judicious use of the results can shorten the development cycle. The difficulty in generalizing the response of systems in an EMP environment is well demonstrated by the damage constant histogram of figure 27.

[2] *D. M. Tasca, J. C. Peden, and J. L. Andrews, Theoretical and Experimental Studies of Semiconductor Device Degradation Due to High Power Electrical Transients, General Electric Document No. 73SD1289 (December 1973).*

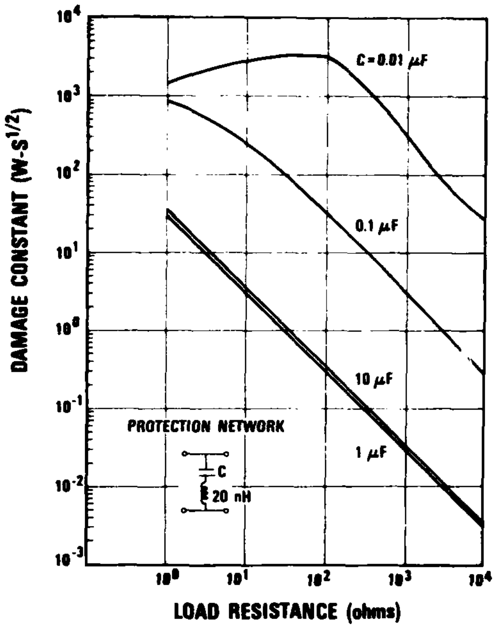


Figure 3. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 0.1 km at 5 m, far end open, broadside illumination.

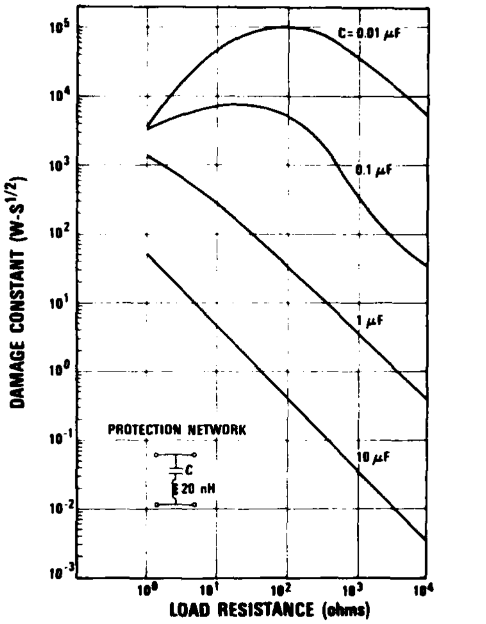


Figure 5. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 1 km at 5 m, far end open, broadside illumination.

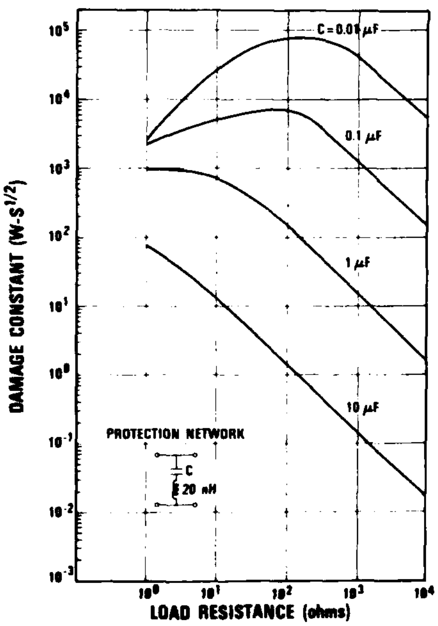


Figure 4. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 1 km at 5 m, far end shorted, broadside illumination.

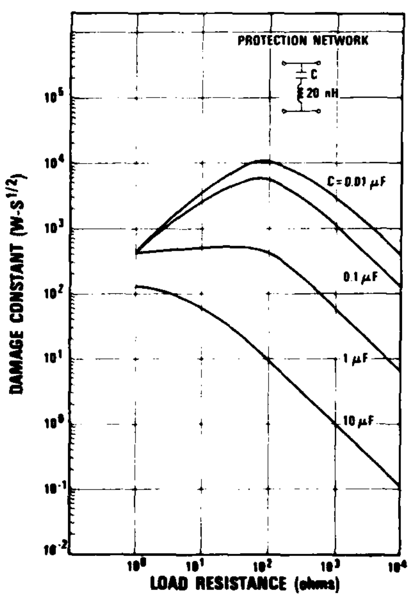


Figure 6. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 5 km on ground, far end open, broadside illumination.

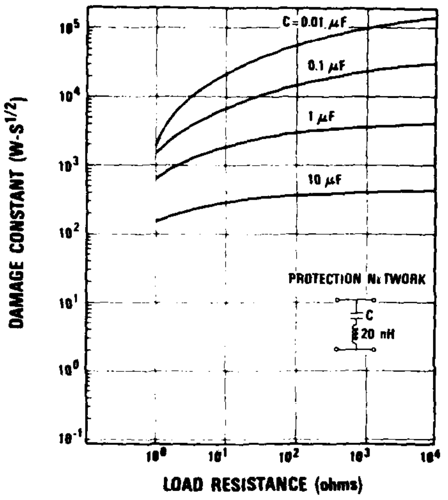


Figure 7. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, broadside illumination.

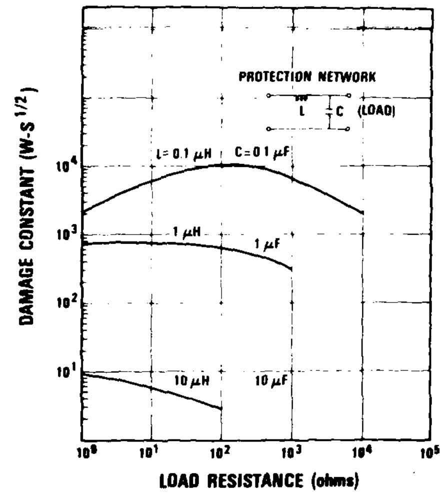


Figure 9. Damage response of circuit load for two-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, broadside illumination.

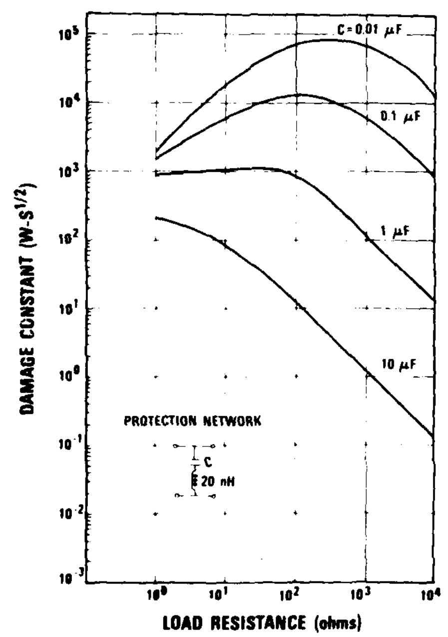


Figure 8. Damage response of circuit load for single-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end shorted, broadside illumination.

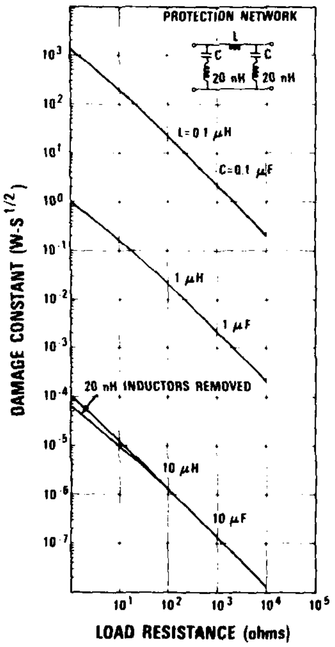


Figure 10. Damage response of circuit load for three-stage filter protection network for following open-wire parameters: 0.1 km at 5 m, far end open, broadside illumination.

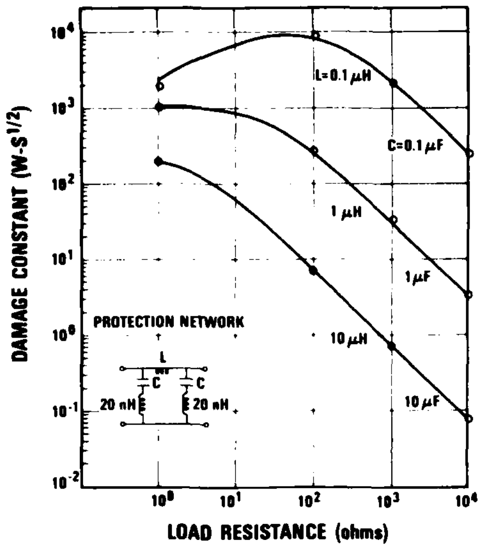


Figure 11. Damage response of circuit load for three-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end shorted, broadside illumination. Open circles represent response with the 20 nH inductors removed from protection network.

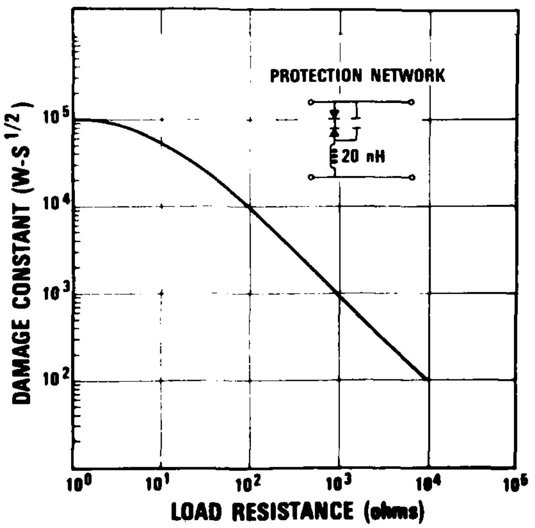


Figure 12. Damage response of circuit load for simulated zinc-oxide surge arrester protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

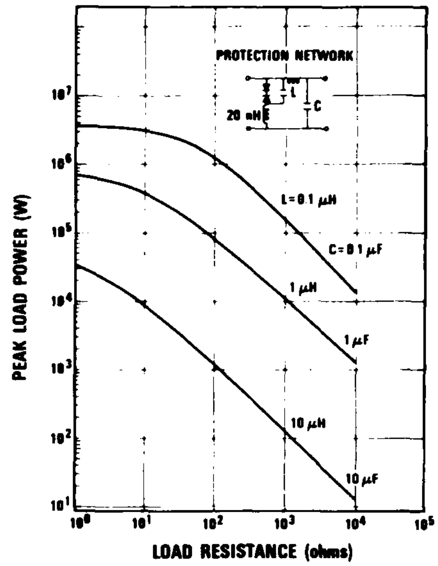


Figure 13. Peak load power for simulated zinc-oxide surge arrester and two-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

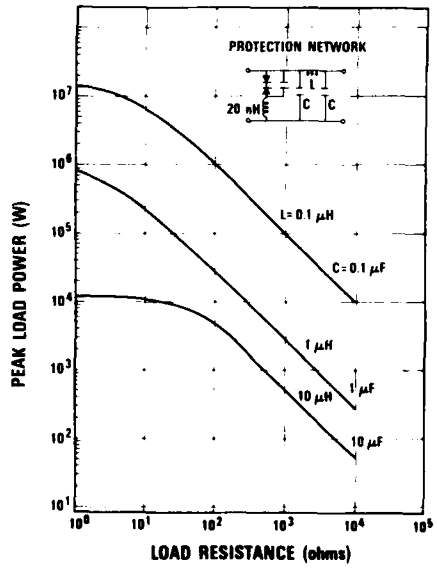


Figure 14. Peak load power for simulated zinc-oxide surge arrester and three-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

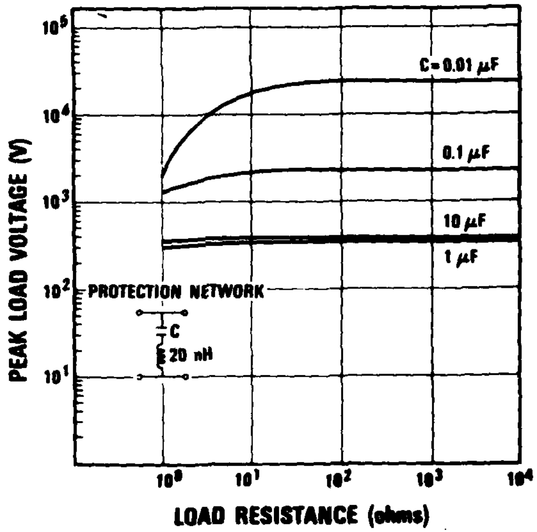


Figure 15. Peak load voltage for single-stage filter protection network for following open-wire parameters: 0.1 km at 5 m, far end open, broadside illumination.

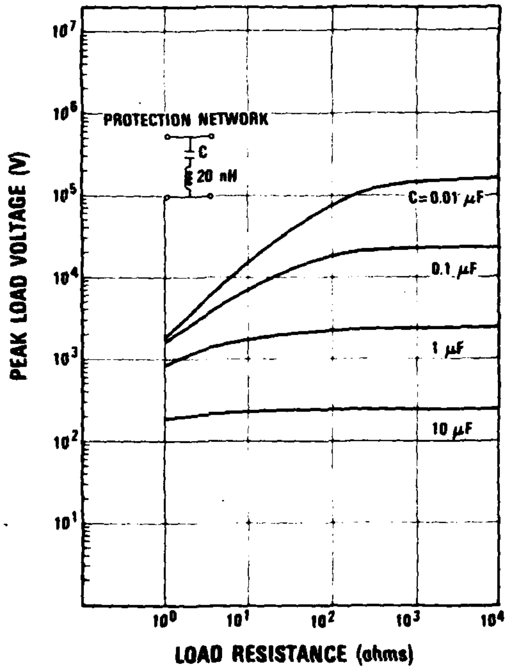


Figure 16. Peak load voltage for single-stage filter protection network for following open-wire parameters: 1 km at 5 m, far end shorted, broadside illumination.

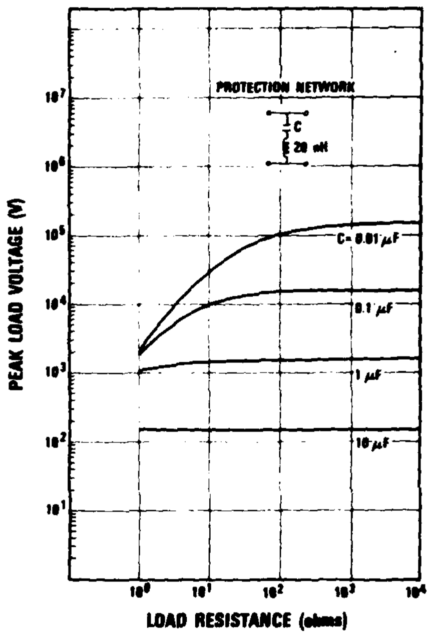


Figure 17. Peak load voltage for single-stage filter protection network for following open-wire parameters: 1 km at 5 m, far end open, broadside illumination.

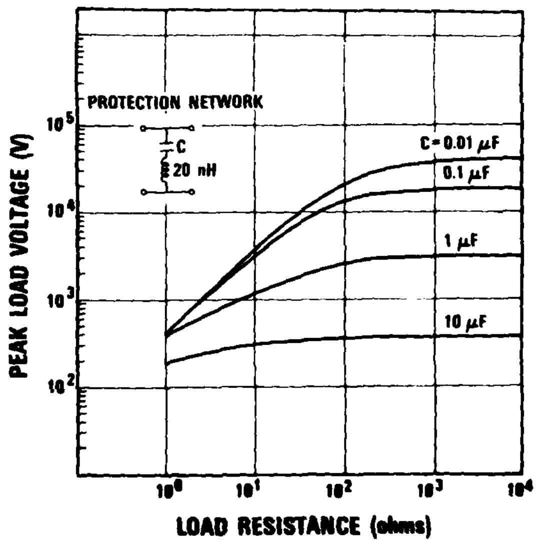


Figure 18. Peak load voltage for single-stage filter protection network for following open-wire parameters: 5 km on ground, far end open, broadside illumination.

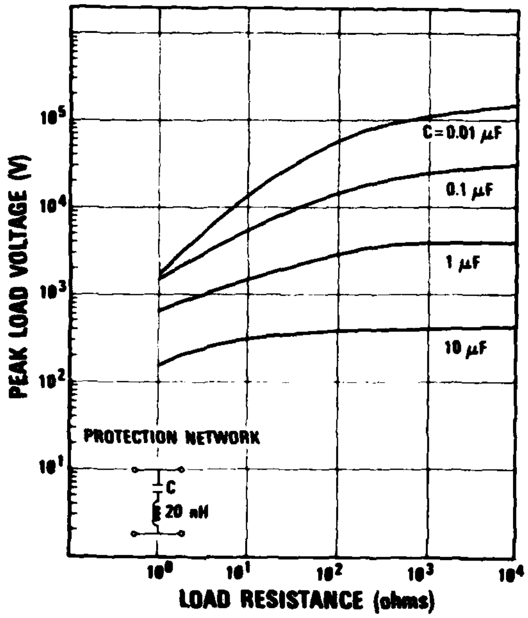


Figure 19. Peak load voltage for single-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, broadside illumination.

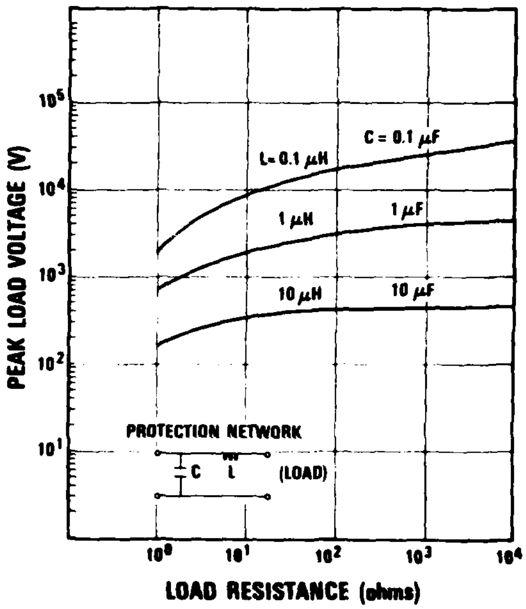


Figure 21. Peak load voltage for two-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, broadside illumination.

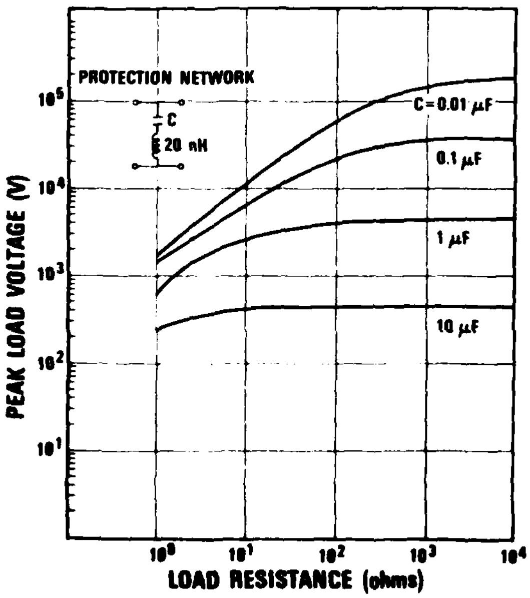


Figure 20. Peak load voltage for single-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end shorted, broadside illumination.

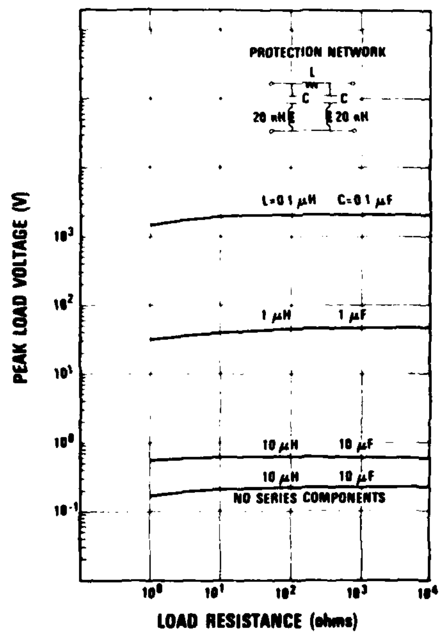


Figure 22. Peak load voltage for three-stage filter protection network for following open-wire parameters: 0.1 km at 5 m, far end open, broadside illumination.

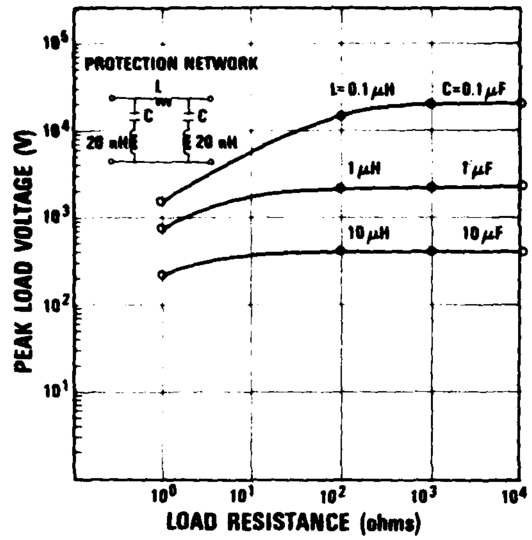


Figure 23. Peak load voltage for three-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end shorted, broadside illumination. Open circles represent response with the 20 nH inductors removed from protection network.

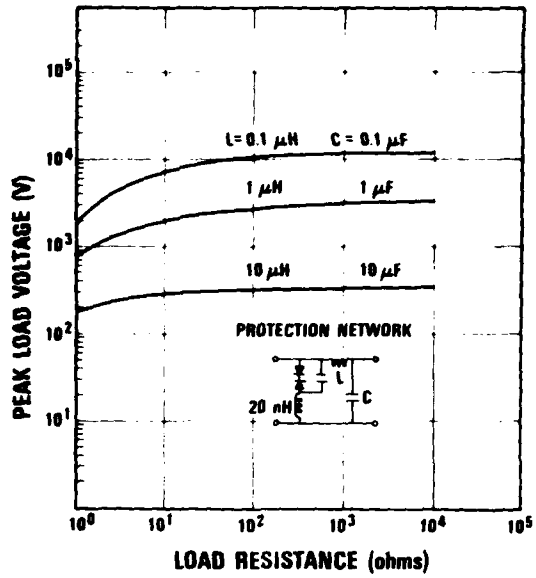


Figure 25. Peak load voltage for simulated zinc-oxide surge arrester and two-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

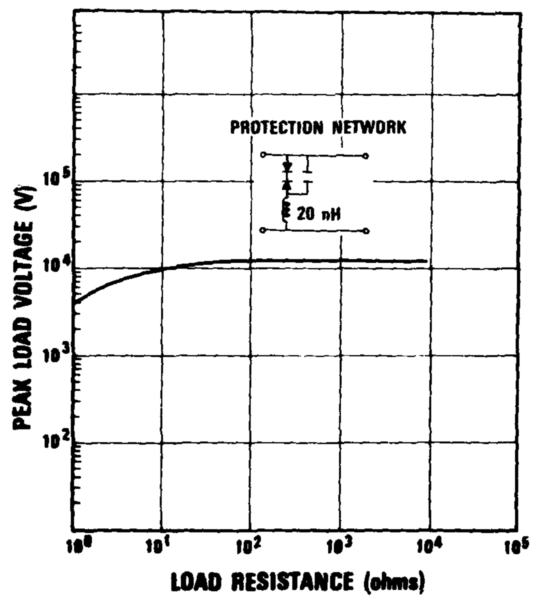


Figure 24. Peak load voltage for simulated zinc-oxide surge arrester protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

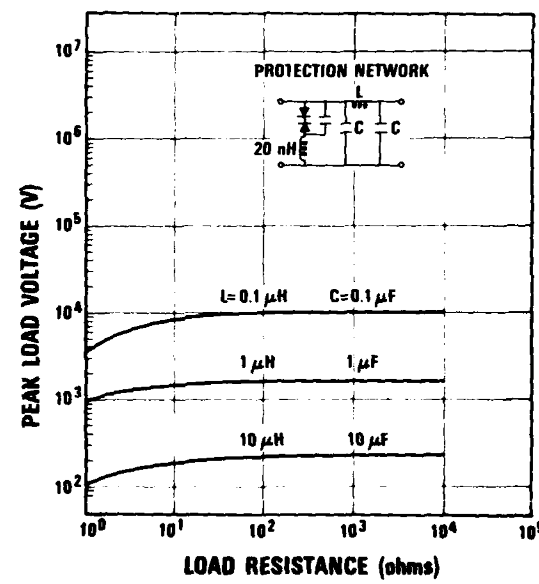


Figure 26. Peak load voltage for simulated zinc-oxide surge arrester and three-stage filter protection network for following open-wire parameters: 5 km at 5 m, far end open, end-on illumination.

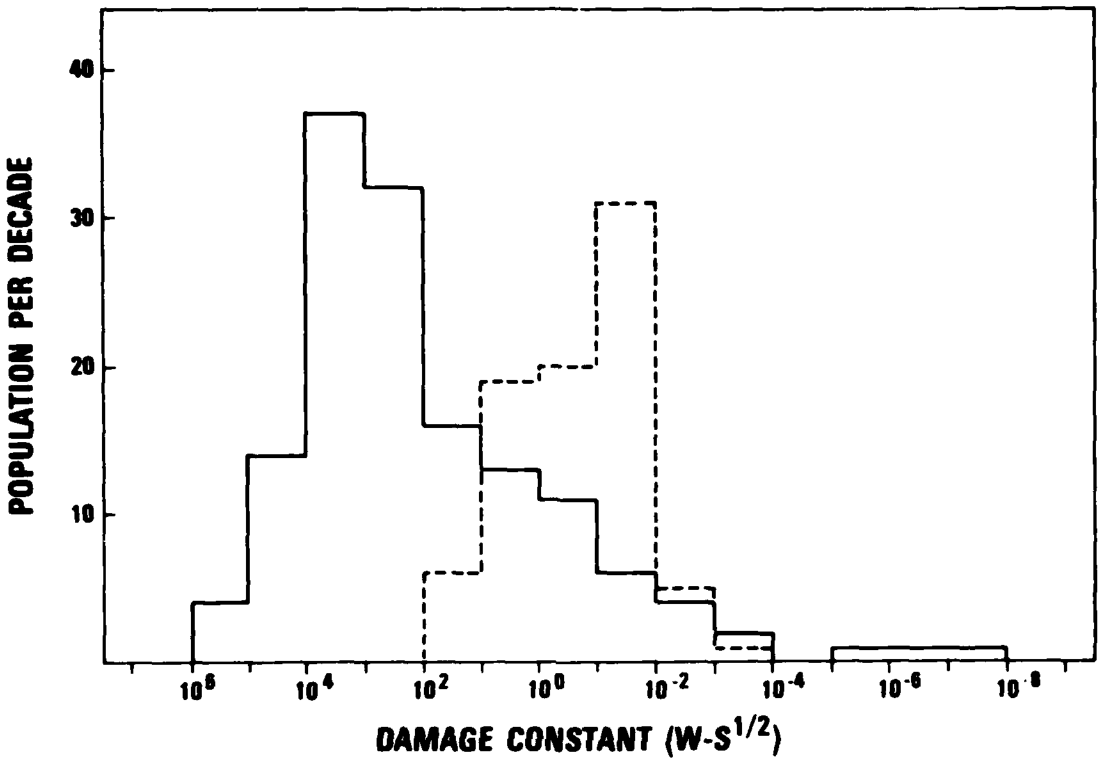


Figure 27. Damage constant histogram for data of figures 3 through 12 with superimposed histogram *(dashed curve)* of damage constants of 51 diode and transistor types.

APPENDIX A — Diode and Transistor Types Included in Damage Survey

1N3025B	2N3439
1N2991B	2N3375
MO1054	2N3013
MS1040	2N2894
FS5961-947-8901	2N2857
1N2580	2N1613
1N1731A	2N1490
1N1202AR	2N1485
1N751A	2N1042RA
1N746A	2N706
1N645	2N705
1N485B	2N501A
1N277	2N466M
FS911-3465	2N428M
1N4384	2N396A
1N3016B	2N393
1N4141	2N297A
1N270	2N328A
1N752A	2N335
1N914A	2N404A
1N3026B	2N930
1N3611	2N2222A
CA3018	2N2481
2N5829	2N2484
2N3584	2N2907A
	2N3736

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